A DISK EMG SYSTEM
FOR DRIVING IMPACTING LINERS TO ~ 20 km/s

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Abstract

We consider an ALT-1,2-like [1,2] system to deliver up to 60-70 MA currents in the liner load and accelerate ~20 g/cm cylindrical liners to ~20 km/s (ALT-1,2: ~31 MA, ~13 g/cm, ~12 km/s). The system is intended for the ALT-3 experiment to test the efficiency of magnetic implosion of impacting liners and to verify the possibility of shock-wave measurements at up to 1 TPa pressures.

We describe the physical configuration of the system and its diagnostic suite, which differ significantly from similar systems [3,4]. As compared with [4], changes are made to the physical configuration of individual system units and a number of system parameters: we increase load inductance by a factor of 1.5, use a different transmission line and an Al liner (instead of envisaged two-layer liners) etc.

Simulated characteristics of the system are presented.

I. INTRODUCTION

Magnetic implosion of cylindrical liners in the Z-pinch geometry is of interest for high energy density physics, in particular, for producing terapascal shock pressures in various materials [1-4]. Pulsed power drivers based on disk explosive magnetic flux compression generators (DEMG) with electrically exploded fuse opening switches (FOS), similar to the systems used in the previous experiments, can deliver up to 60-70 MA currents with a characteristic rise time of 1-2 μs, which makes it possible to accelerate up to ~ 20 g/cm liners to ~ 20 km/s [2-4]. Al and two-layer liners are considered, which, as predicted by 1D simulations, can produce up to 1-3 TPa shock pressures, when accelerated to the above velocities [3,4].

In the ALT-1,2 experiments (Advanced Liner Technology, 1999-2000, Fig. 1a) [1] with a 10-module 0.4 meter diameter DEMG, peak currents in the liner ponderomotive unit (PU) reached 31-32 MA. A cylindrical Al liner of 4 cm height, 4 cm radius and 0.2 cm thickness (~ 13g/cm mass), driven by a ~ 2 MG magnetic field, impacted a 2 cm diameter central measuring unit (CMU) at a velocity of $v_{imp} \approx 12$ km/s.

As a driver for the magnetic implosion of larger-mass liners in [3,4] we considered similar but more efficient systems with a 15-module 0.4 meter diameter DEMG. In the systems discussed in [4] (Fig. 1b), the values of current, energy and power delivered to the liner load can reach ~ 70 MA, ~ 40 MJ and ~ 20 TW; these are a factor of ~2, ~ 4 and ~ 7, respectively, higher than in the ALT-1,2 systems. The high compared to [1] efficiency of these systems is basically associated with low load inductance (~ 4 nH, which is a factor of ~ 2 lower than in ALT-1,2) and small losses in PU (PU height is reduced from 15 to 6 cm, and thin Al return current conductor in PU is replaced with a thick Cu one, Figs. 1a,b). In these systems, with PU currents of ~ 70MA (magnetic fields of ~ 5MG), ~20 g/cm liners can impact the 2 cm diameter CMU at a velocity of $v_{imp} \approx 20$ km/s. According to 1D magnetohydrodynamic (MHD) simulations, ~ 40 percent of mass of such liners adjacent to their front surface remains solid and dynamically hardened, which allows us to hope that this will suppress the growth of their Rayleigh-Taylor-like instability. In the ALT-3 experiment, we are planning to use a system with an explosive closing switch (ECS), in which the liner instability can be expected [5] to grow less intensively than in a system without ECS, and with a 3 mm thick Al liner, which is less unstable than a two-layer liner of the same mass. Liner instability and liner / glide plane interaction during implosion are studied by 2D MHD simulations (e.g. [5]).

Simulations of the systems [1-4] with two types of explosive, "old" [1,2] and "new" [3,4,6], were performed using the 1D(MHD)n code [7] developed based on the UP-OK technique [8]. In this code, all major units of these systems are simulated taking into account their geometry

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14. ABSTRACT
We consider an ALT-1,2-like [1,2] system to deliver up to 60-70 MA currents in the liner load and accelerate ~20 g/cm cylindrical liners to ~20 km/s (ALT-1,2: ~31 MA, ~13 g/cm, ~12 km/s). The system is intended for the ALT-3 experiment to test the efficiency of magnetic implosion of impacting liners and to verify the possibility of shock-wave measurements at up to 1 TPa pressures. We describe the physical configuration of the system and its diagnostic suite, which differ significantly from similar systems [3,4]. As compared with [4], changes are made to the physical configuration of individual system units and a number of system parameters: we increase load inductance by a factor of 1.5, use a different transmission line and an Al liner (instead of envisaged two-layer liners) etc. Simulated characteristics of the system are presented.

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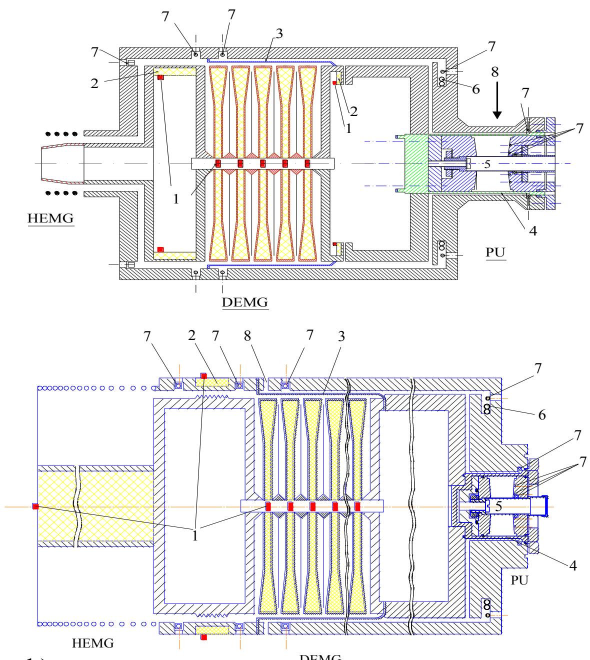
and materials by joint calculation of an arbitrary number (n) of 1D MHD problems coupled by means of boundary and other conditions. The accuracy of current predictions for the systems is close to the accuracy of current measurements by B-dot probes (±5%). Such a close agreement between simulated and experimental currents (and current waveforms) allows us to employ the combined experimental and computational approach for a detailed analysis of FOS characteristics, including various regimes of electric explosion of the Cu foil [9], as well as characteristics of ECS and the system as a whole in already conducted [1,10] and envisaged [2-4] experiments.



b)

Figure 1. Schematic drawings of the systems and their diagnostic suites in ALT-1,2 [1] (a) and in [4] (b).
1 – detonators; 2 – ECS; 3 – FOS;
4 – liner; 5 – CMU;
6 and 7 – Faraday and B-dot probes;
8(a) – radiographic equipment;
8(b) - place to install ECS in the load.

In this paper we consider a system similar to [4], being developed at VNIIEF for the ALT-3 experiment to test the efficiency of high-velocity (~20 km/s) implosion of an impacting Al liner and the possibility of measuring shock-wave time intervals in reference samples (Al) at up to 1TPa pressures. As compared with [4], modifications have been made to the physical configuration of individual system units and a number of system parameters. Appropriateness of these modifications has been revealed at the design stage and, as provided for in [4], based on the results of 2D MHD simulations of liner implosion [5].

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II. PHYSICAL CONFIGURATION AND BASIC PARAMETERS OF THE ALT-3 SYSTEM

The system of interest (Fig. 2) comprises the following basic functional units and is characterized by the following basic parameters.

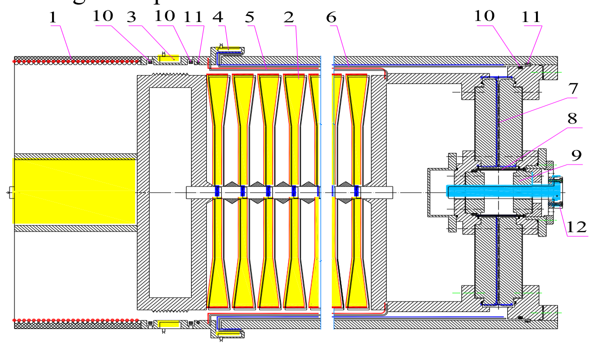


Figure 2. Schematic drawing of the ALT-3 system and its diagnostic suite.

1. Helical EMG (HEMG), preamplifier: supplies initial magnetic flux (current I_0) to DEMG by the time t_0, when magnetic flux compression begins in DEMG;
2. 0.4 meter diameter DEMG, amplifier, with N=15 modules and “new” explosive [3];
3. Explosive switch (crowbar): disconnects HEMG from DEMG;
4. ECS: connects the load to FOS at a given time t_{0l} (at a given FOS voltage U_{0l}), is characterized by effective ohmic resistivity Ω_l;
5. FOS: an electrically exploded fuse switch in the load, which is a cylindrical Cu foil having a thickness of Δ_f and height H_f installed in DEMG’s coaxial line;

6,7. Coaxial-radial transmission line (CTL and RTL) of inductance L_{0l} with high-voltage protection from the Cu foil to the PU liner; it also provides angular symmetrization of the PU current;

8. PU’s cylindrical Al liner of outer radius R_l, effective height H_l (for implosion) and "current” height $H_{pu} > H_l$ (between Al liner contacts with the PU’s Cu return conductor);
9. PU’s Cu glide planes (electrodes): proper choice of their geometry and material provides experiment-appropriate liner / CMU impact synchronism disturbed by liner / glide plane interaction during implosion;

10,11. B-dot and Faraday probes: measure current time derivatives and current waveforms in HEMG, DEMG, TL and PU, including assessment of angular current asymmetry;

12. CMU: serves to measure impacting liner implosion efficiency and test the possibility of shock-wave measurements in samples.

Let us note the basic modifications made to the physical configuration and parameters of the system compared to [4] (Figs. 2 and 1b).

Changes have been made in the TL's radial part (RTL) to enable assembly of its major current conductors, polyethylene (CH_2) insulator, liner PU, and CMU as a single precision system. The CH_2 insulator in RTL and the major coaxial insulator in CTL are in contact with glycerol occupying the expanded RTL-to-CTL transition. Such insulation from the FOS foil to the PU liner can be reliable enough, as demonstrated by simulations and high-voltage tests of material transitions in the insulation. For example, for a peak FOS voltage of $U_f \approx 300$ kV, simulated peak electric fields on the TL insulators are the following: ~ 120 kV/mm (basic 2.5 mm thick mylar/glycerol insulator in CTL), ~ 40 kV/mm (2 mm CH_2 insulator in RTL), ~ 5 kV/mm (~ 25 mm glycerol in RTL-to-CTL transition).

Load inductance L_{0l} has been increased from ~ 4 to ~ 6 nH. This led to the reduction of the Cu foil thickness Δ_f from ~ 0.18 to 0.12 – 0.15 mm and modification of other system parameters to some degree in order to reduce FOS peak voltages and ensure the required PU current.

The shape of the PU glide planes has been chosen based on the results [5] of 2D MHD liner implosion simulations. The slope of the PU glide planes is reduced from 6^0 to 0^0, and the size of stepped 4mm × 4mm grooves is the same as in ALT-1,2 (Figs. 2 and 1a).

To test the impacting efficiency of the Al liner having a thickness of 3 mm and previous radius and height of $R_l \approx H_l \approx 4$ cm, up to 32 PDV probes [11] are installed in CMU. These probes are used to measure the velocity of the liner's front surface and synchronism of liner impact against the 2 cm diameter CMU and to test the possibility of accurate enough shock-wave measurements in reference samples (Al).

Compared to [1,10], the physical configuration of ECS provides smaller losses, $\Omega_l \leq 0.2$ mΩ. In addition, it requires smaller, compared to [1, 10], FOS voltages, $U_{0l} \leq 10$ kV, by the time of actuation t_{0l} (this precludes interference with diagnostic equipment). As a result, the PU current and its rise time will increase.

III. SIMULATED CHARACTERISTICS OF THE ALT-3 SYSTEM

As evidenced by 2D (MHD) simulations with currents twice as high as in [1] (Fig. 3), the standard connection between the Al liner and the PU's Cu return conductor (Fig.2, item 8) is reliable and operates without considerable plasma formation.

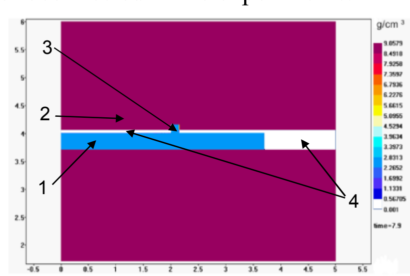
The system as a whole was simulated using the $1D(MHD)_n$ code (see Introduction and Fig.2); simulation results are presented in Table 1 and in Figs. 4-7 (time measured from the time t_0).

It follows from Table 1 that for the FOS Cu foil thickness of 0.12 mm, simulations produce the lowest FOS peak voltages, U_{fm} = 224-257kV, for all the system parameters considered. PU peak currents I_{lm} and maximum liner velocities v_{imp} lie in the ranges of 59-66 MA and 19.0-21.9 km/s, and required ECS actuation times are t_{0l} = 14.5 - 15.3 - 16.1 - 16.7 µs at currents I_0 = 7.5 7 - 6.5 - 6 MA, respectively. If the foil thickness is Δ_f = 0.15 mm, then FOS voltages reach U_{fm} = 288-357kV, while currents I_{lm} and liner velocities v_{imp} grow insignificantly, cf. systems 1 and 2, 3 and 4.

Figs. 4a,b show simulated time profiles of Al liner implosion characteristics in systems 1 and 2 for the current I_0 = 7MA. Liner currents in these simulations reach peak values of ~ 65 and ~ 71 MA with a magnetic field on the liner's back surface of ~ 4 MG, when the liner moves at a distance of ~ 10 and ~ 8 mm, respectively (magnetic fields by the end of liner implosion reach ~ 5.5 MG).

Simulated efficiency of the system is rather high: peak FOS voltage can reach 230 – 300 kV (Δ_f = 0.12 – 0.15 mm, I_0 = 7 MA); peak power and maximum electromagnetic energy transferred through FOS to the load is W_f = 14-15 TW and S_{fm} ~ 35 MJ, - which is a factor of ~ 5 and ~ 3.5 higher than in ALT-1,2 and a factor of ~ 1.5 and ~ 3.5 higher than in [10], see Figs. 5a,b and Table 2.

Note that these experiments provided for "slow" and "fast" regimes of FOS Cu foil electric explosion with foil thicknesses of Δ_f = 0.12 and 0.155mm and foil voltages of $U_{fm} \approx 200$ and 430 kV: $j^2_{fm} \approx 420$ and 830 MA^2/cm^4 and w_{fm} = 4.4 and 7 GW/g, respectively (Table 2). In the system under consideration, electric explosion regimes for the same Cu foil thickness (Δ_f = 0.12 – 0.15 mm) are "slow" (Figs. 6a,b): $j^2_{fm} \approx 270$ - 500 MA^2/cm^4 and w_{fm} = 2.9-6.4 GW/g. The slowest of these regimes (Δ_f = 0.12 mm) has not been tested in the experiments.



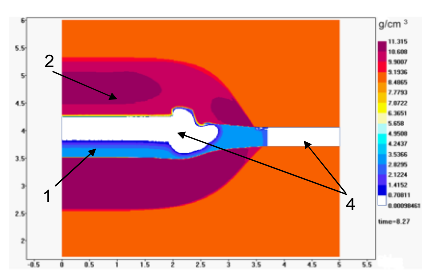
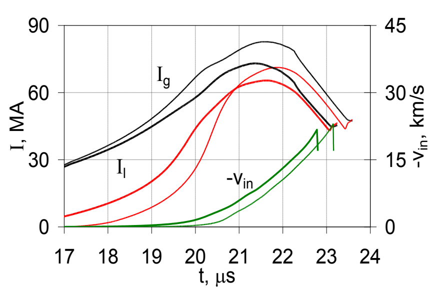


Figure 3. Density isolines from 2D MHD simulations of the connection between the Al liner (1) and the Cu return conductor (2) in the initial state (top) and ~ 10 µs after reaching the peak current of ~ 66 MA (bottom).
3 – Al contact ring, 4 – vacuum gaps.

Table 1. Simulated characteristics of the ALT-3 system for possible values of its parameters U_{0l} = 8kV, Ω_l = 0.2mΩ, I_0 = 7.5 - 6.0MA, Δ_f = 0.12mm or 0.15mm, and L_{0l} = 6nH (systems 1 and 2) or 7nH (systems 3 and 4)

#	I_0 MA	Δ_f mm	t_{0l} μs	U_{fm} kV	I_{gm} MA	I_{lm} MA	v_{imp} km/s
1	7.5	0.12	14.5	246	74.6	66.1	21.9
	7.0	0.12	15.3	233	73.0	65.4	21.7
	6.5	0.12	16.1	224	71.0	64.2	21.0
	6.0	0.12	16.7	237	68.5	62.4	19.8
2	7.5	0.15	16.7	288	85.1	72.6	23.7
	7.0	0.15	17..2	304	82.7	71.2	23.0
	6.5	0.15	17.6	315	79.8	69.2	22.0
	6.0	0.15	18.1	320	76.4	66.4	20.8
3	7.5	0.12	14.5	231	71.0	63.5	21.4
	7.0	0.12	15.3	225	69.5	62.5	20.9
	6.5	0.12	16.1	238	67.4	61.1	20.0
	6.0	0.12	16.7	257	64.9	59.2	19.0
4	7.5	0.15	16.7	313	81.5	68.8	22.7
	7.0	0.15	17.2	333	78.6	67.1	21.9
	6.5	0.15	17.6	349	75.6	64.8	20.8
	6.0	0.15	18.1	357	72.3	62.0	19.6

Designations in Table 1: U_{fm} , I_{gm}, I_{lm} are Cu foil peak voltages, DEMG and load (PU) peak currents; t_{ol} is ECS actuation time; v_{imp} is liner / CMU impact velocity.



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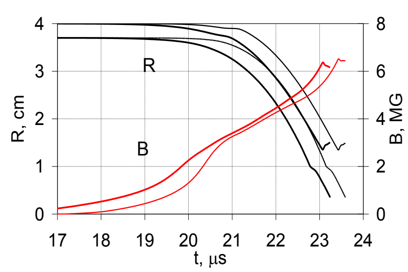
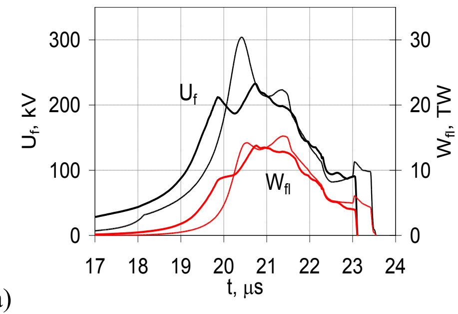


b)

Figure 4. Simulated DEMG and load currents, I_g and I_l, velocity of the liner's front surface v_{in} (a); radii of both liner surfaces (R_{in}, R_{out}) and magnetic field B_{out} on the liner's back surfaces (b), - for the system with foil thicknesses of 0.12 and 0.15 mm (thick and thin lines, systems 1 and 2 with I_0 = 7 MA, Table 1).



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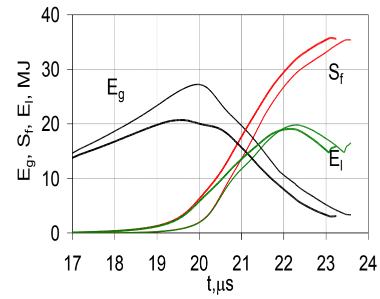
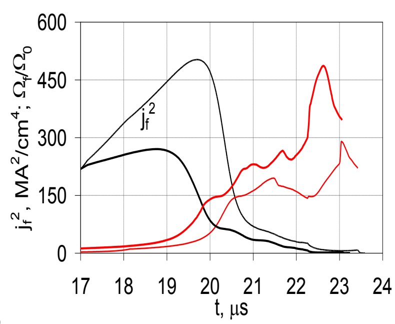


b)

Figure 5. Simulated FOS voltage U_f (a), power W_f (a) and electromagnetic energy flux S_f delivered through FOS to the load, magnetic energies E_g and E_l in DEMG and in the load (b), - for the system with foil thicknesses of 0.12 and 0.15 mm (thick and thin lines, systems 1 and 2 with I_0 = 7 MA, Table 1).



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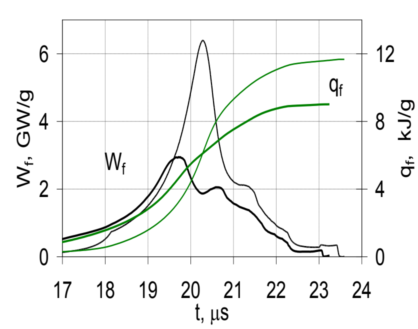

b)

Figure 6. Simulated squared current density j^2_f and effective relative resistivity Ω_f/Ω_0 (a), specific power w_f and Joule heating of the FOS Cu foil q_f (b), - for the system with foil thicknesses of 0.12 and 0.15 mm (thick and thin lines, systems 1 and 2 with I_0 = 7 MA, Table 1).

Simulated profiles of MHD quantities in the Al liner before the liner / CMU impact (Fig. 7a,b) show that ~ 48 and ~ 45 percent of liner mass for Δ_f = 0.12 and 0.15 mm (systems 1 and 2 with I_0 = 7 MA) remains solid. This part of the liner satisfies the solid-state criterion based on the yield strength (Y > 0), and the temperature lies in the following range (Fig. 7b): 0.04 eV $\leq T < T_m \approx$ 0.31 eV. Here, T_m is the melting point (Y=0 at $T \geq T_m$), which is considerably higher than that of aluminum under normal conditions, T_{om} = 0.08 eV, due to high (a factor of ~1.5) compression of aluminum. Magnetic fields near the back surface of Al reach ~ 5.5 MG, and maximum temperatures, ~ 16 eV, (Fig. 7a, the regions near the back surface are cooled due to heat conductivity and radiation). According to the 1D simulations, such impacting liners can produce up to ~ 1 TPa shock pressures in reference samples (Al, Fig. 7c).

Table 2. Simulated FOS performance in systems with N-module 0.4 meter diameter DEMG with FOS and ECS, from [1,4,9,10] and current paper (italics).

N (I_0, MA)	10 (6) [1,9]	15(6) [10,9]	15(7) [4]	*15(7)*
Δ_f, mm H_f, cm	0.12 72	0.155 108	0.18 108	*0.15-0.12* *90*
U_{ol}, kV L_{0l}, nH H_{pu} (Z)cm M_l, g	~ 50 8 15(Al) 45	~100 10 2(Cu) 1	30 4 6(Cu) 75	*8* *6* *6.6(Cu)* *75*
v_{imp}, km/s	12	~50	23	*23-21.7*
E_{gm}, MJ	10	-	33	*27-21*
U_{fm}, kV	200	430	250	*300-230*
I_{lm}, MA	32	36	73	*71-65*
W_{fm}, TW	3	10	17	*15-14*
S_{fm}, MJ	10	10	39	*35-36*
E_{lm}, MJ	5	6	13	*20-19*
$\Omega_f(U_{fm})/\Omega_f(0)$	120	130	140	*130-120*
w_{fm}, GW/g	4.4	7	4.7	*6.4-2.9*
j^2_{fm}, MA^2/cm^4	420	830	630	*500-270*

Designations in Table 2: N (I_0, MA) is the number of DEMG modules and feed current; Δ_f, H_f are thickness and height of the Cu foil in FOS; U_{ol} is FOS voltage to connect the load of inductance L_{0l} ; H_{pu} (Z) is the PU height (return conductor material), M_l and v_{imp} are liner mass and maximum velocity; U_{fm} and I_{lm} are peak FOS voltage and peak PU current; W_{fm} and S_{fm} are peak power and maximum electromagnetic energy transferred through FOS to the load; E_{gm} and E_{lm} are peak magnetic energies in DEMG and in the load; $\Omega_f(U_{fm})/\Omega_f(0)$ is relative foil resistivity at peak foil voltage; w_{fm} and j_{fm} are peak values of specific power of Joule heating and current density in the foil.

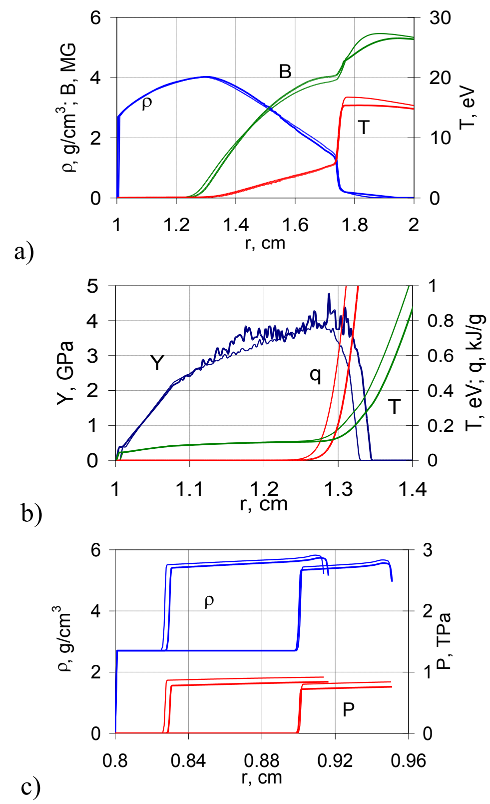

Figure 7. Simulated distributions along the Al liner radius of density ρ, magnetic field B, temperature T, Joule heat q and yield strength Y before liner/CMU impact (a, b); profiles of density and shock pressure in the Al target (c), in the system with Δ_f = 0.12 mm and Δ_f = 0.15 mm (thick and thin lines).

IV. CONCLUSION

The paper presents the physical configuration, basic parameters and simulated characteristics of the ALT-1,2-like system for the ALT-3 experiment. The purpose of the experiment is to test the efficiency of magnetic implosion of an impacting cylindrical Al liner and the possibility of shock-wave measurements in Al samples at up to 1 TPa pressures using PDV probes installed at an impact radius of ~ 1 cm.

As predicted by the simulations, the proposed pulsed power system will have high efficiency: peak power and electromagnetic energy transferred through FOS to the load can be as high as ~ 15 TW and ~ 35 MJ; this is a factor of ~ 3 and ~ 3.5 higher than in ALT-1,2, with the number of DEMG modules increased from 10 to 15.

Systems parameters, which were used as initial data for simulations and will possibly be used in the experiment, are the following: load inductance 6 – 7 nH, FOS foil thickness 0.12 - 0.15 mm, initial DEMG current 6.0 – 7.5

MA. According to these simulations, DEMG current, FOS voltage, PU current and velocity of a 4 cm radius 3 mm thick Al liner can reach 65 – 85 MA, 225 – 357 kV, 59 – 73 MA and 19 – 23 km/s, respectively. As shown by the 1D MHD simulations, up to ~ 50 percent of liner mass can remain solid and suppress the growth of liner instability, which needs to be verified by 2D MHD simulations.

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